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Numerical estimation of AC loss in superconductors with ripple current

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Abstract

The loss energy density (AC loss) with ripple current is numerically calculated by finite element method for cylindrical and strip superconductors based on Irie-Yamafuji model in which the magnetic field dependence of the critical current density is taken into account for design of DC transmission cable system. It is confirmed that calculated result of the AC loss in the cylindrical superconductor with the ripple current agrees well with theoretical estimation which was reported in the previous work. On the contrary, the AC loss in the strip superconductor with the ripple current is obtained only by numerical calculation. It is found that the AC loss in the strip superconductor of the ripple current becomes larger than that without DC current at small ripple current amplitude, since the penetration depth of magnetic field

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becomes large. Therefore, it is recommended that strip superconductor is better to use as cylindrical hollow superconductor for DC transmission cable system to reduce the AC loss.
Keywords: DC transmission cable; AC loss; ripple current; Irie-Yamafuji model; cuprate high temperature superconductor; cylindrical and strip superconductors

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1. Introduction

DC transmission cable by cuprate high temperature superconductor has been developed, since its loss energy density (AC loss) is considerably smaller than that in AC transmission cable, and it is considered to be suitable for long distance energy transmission [1, 2]. In addition, it was recently reported that the transport critical current of DC transmission cable can be enhanced by using longitudinal magnetic field effect, resulting in compact size compared with AC transmission cable [3].

However, the existing conventional transmission power system is based on AC. It is necessary to convert current from AC to DC and vice versa with very large inductance in the current-source converter circuit for installing DC transmission cable. This current conversion system is one of the reasons to increase the cost for instalation of DC transmission cable for practical usages. Therefore it is desired to estimate the AC loss for the case of DC and superposed AC (ripple current) for design of DC transmission cable system. If the AC loss of ripple current on DC is small enough than the cooling capacity, the ripple current is allowed, resulting in the reduction of the size of inductance for conversion system from AC to DC.

In our previous work the AC loss in cylindrical superconductor is theoretically estimated based on Irie-Yamafuji model [4]. The magnetic field dependence of the critical current density is taken into account in Irie-Yamafuji model, and it is more realistic than using simple Bean-London model in which the magnetic field dependence of the critical current density is ignored. It was found that there is the AC current amplitude region where AC loss becomes smaller than that for pure AC current, i.e. without DC. It was concluded that the AC loss of ripple current is small enough in the layered structure of the DC transmission cable made by the thin superconducting tapes, i.e. superconductor is cylindrical hollow shape.

Although the theoretical estimation is very important, it is necessary to study the numerical calculation, since it is more flexible for a design of DC transmission cable. For example, it is very difficult to estimate AC loss taken into account of the effect of the magnetic field dependence of the critical current density for a single strip superconductor. Therefore, it is important to estimate AC loss for a strip superconductor even if it is not practical usage, since any kinds of calculations with strip superconductors will be possible. It should be noted that AC loss of a single strip superconductor is larger and is not suitable for DC transmission cable, since the flux lines mainly penetrate from the edges of the strip.

In this study, the AC losses in superconductors are numerically calculated by using finite element method (FEM). The numerically calculated result is confirmed to be equal to the theoretical result for the case of a cylindrical superconductor. The AC loss for the case of a strip superconductor is also calculated by FEM for confirmation of validity of using FEM for numerical calculation.

2. Calculations

AC loss with ripple current was calculated by finite element method (FEM) which is commercial software Photo-Eddy developed by Photon Ltd, Japan. The model for cylindrical superconductor is 5 degree model with radius of 1.3 mm to reduce the number of elements in calculation due to the symmetrical condition. The thickness of the superconductor is 0.3 mm, since the flux penetrates only from the surface of the cylindrical superconductor. The superconductor region is divided in elements with size of 2–6 μm according to the maximum value of current. The total number of elements is 2,400 and the total number of nodes is 5,061. The present model is different from a real DC transmission cable. However, it is easy to calculate for other cases by FEM, since the symmetrical condition is satisfied for the case of cylindrical superconductor.

On the other hand, it seems to become difficult in the case of strip superconductor. The cross section of the strip superconductor calculated in the present study is 3 mm $\times$ 2 μm. The point for adequate calculation in FEM is the aspect ratio between the width and the thickness of the element. The aspect ratio should be less than 1000 for both superconductor and air regions. It is also required that the size difference between neighbor elements should be small enough. Therefore, the number of the elements is about 76,000 and the total number of nodes is about 105,000.

The AC loss calculation for the single strip superconductor seems to be meaningless, since the AC loss is large due to the large penetration of flux lines from the edges of the strip, and the many strip superconductors are used as a cylindrical hollow shape. However, the calculation of the AC loss of the single strip superconductor by FEM is very difficult but useful for applying any kinds of power transmission cable made by strip superconductors in future works.

The magnetic field dependence of the critical current density is given based on Irie-Yamafuji model as

$$J_{\mathrm{c}} = \alpha_{\mathrm{c}} B^{\gamma-1}, \tag{1}$$

where α_{c} and γ are pining parameters [5]. If γ equals to unity, the model is correspond to Bean-London model in which the magnetic field dependence of the critical current density is ignored. In the present calculation, $\alpha_{\mathrm{c}} = 2 \times 10^{8}$ and $\alpha_{\mathrm{c}} = 1 \times 10^{10}$ are used for cylindrical and strip superconductors, respectively. And $\gamma = 0.5$ is used for both superconductors. The parameters used in FEM calculation is listed in Table 1.

The n-value model is used for describing the nonlinear E-J characteristics of superconductor which is given as

$$E = E_{\mathrm{c}} \left(\frac{J}{J_{\mathrm{c}}} \right)^{n}, \tag{2}$$

where $E_{\mathrm{c}} = 10^{-4}$ V/m is the electric field criterion to determine the critical current density, $J_{\mathrm{c}}(B)$, and $n = 20$ is used for typical case. Further information of using the present FEM code can be found in Ref. [6].

The distributions of the magnetic field, the electric field and the current density in the superconductor are calculated when the DC and superposed ripple current flows the superconductor by FEM which is given by

$$I(t) = I_{\rm DC} + I_{\rm m} \cos \omega t, \tag{3}$$

where $I_{\rm DC}$ and $I_{\rm m}$ are DC and superposed ripple current amplitudes, respectively. The frequency of the superposed AC is 1 Hz, since the numerical result is not so different compared with the case of 50–60 Hz at $n = 20$. In addition, AC loss is not different for the case of higher harmonic frequency which is expected in line commutated converter (LCC), since the AC loss is mainly due to the hysteresis loss and is independent of frequency. Then the ripple loss per unit volume and per cycle W [J/m^3/cycle] is calculated from the product of the electric field and the current density in the superconductor.

3. Results and discussion

First, the calculation by FEM is compared with the theoretical prediction for the case of superconducting cylinder [4], and the validity of the calculation by FEM is confirmed. The calculation of the magnetic field distribution in the superconducting cylinder by FEM is found to coincide with the theoretical prediction. Hence, the calculation by FEM seems to be correct. Fig. 1 shows the example of the calculation of the AC loss of ripple current with and without DC current $I_{\rm DC}$ for the superconducting cylinder based on the calculation of the distribution of the electric field and the current density. In this calculation, the critical current is 2,200 A. Therefore the flux penetration is limited at the surface of the superconductor. This corresponds the calculation for the case of the cylindrical hollow superconductor which is usually used in practical superconducting cable. The agreement between FEM result and theoretical result is satisfied. The AC loss with I_{DC} is larger than that without I_{DC} at $I_{\mathrm{m}} < I_{\mathrm{DC}}$ as predicted by the theory. Therefore, the AC loss of the cylindrical superconductor is confirmed to be calculated by the present FEM code.

Fig. 2 shows the magnetic field distribution in the cylindrical superconductor with various values of n at $I_{\mathrm{m}} = 324$ A and $I_{\mathrm{DC}} = 0$. The magnetic field penetration is larger for the case of small n value. The calculated value approaches according with increasing n to the theoretical prediction which is corresponding to the case of $n = \infty$, i.e. for the case of the critical state model. The difference between the calculated and theoretical values for the typical value in cuprate high temperature superconductor, $n = 20$ is not large enough to cause the large difference in AC loss, since the AC loss is the average value in the superconductor and time. Therefore, it is concluded that the effect of n-value is not seriously significant for the AC loss for typical cuprate high temperature superconductor.

Here, we try to calculate the AC loss for the case of strip superconductor. Fig. 3 shows the AC ripple current amplitude dependence of AC loss of ripple current for the strip superconductor with various I_{DC} for the case of $\gamma = 1$ (Bean-London Model). The critical current is 60 A. The AC loss W is normalized by the AC loss at the critical current, W_{c}, and the AC amplitude I_{m} is normalized by the critical current, I_{c}. The numerical calculations for the case of strip superconductor were studied [7]–[9], and it is known that the calculation for small AC amplitude is difficult by FEM, since the penetration depth of the magnetic field becomes very small [10] and it is difficult to make the model of adequate aspect ratio in elements. Therefore, the calculation is performed at $I_{\mathrm{m}}/I_{\mathrm{c}} > 0.05$ in the present study. It is also reported that the AC loss becomes larger than the prediction value by Norris [11] where the AC amplitude becomes small $I_{\mathrm{m}}/I_{\mathrm{c}} < 0.1$ even at the aspect ratio of 1,000 [12]. This difference causes that the assumption of rectangle strip is not correct but the assumption of ellipse is more suitable for the calculation of AC loss, which is pointed by Clem [12]. It is also found that the AC loss at small amplitude of ripple current is larger than that without DC current as shown in Fig. 3. Since the flux lines do not penetrate from wide surface but mainly from the edges of the strip, the penetration of the flux lines is largely depended on the magnitude of magnetic field at the edges. Therefore, AC loss becomes larger as increasing I_{DC}. This tendency is different from the case of the cylindrical superconductor in which the AC loss is independent of I_{DC} for $\gamma = 1$, since the critical current density is constant.

The magnetic field distribution in strip superconductor for $I_{\mathrm{DC}}/I_{\mathrm{c}} = 0$ and $I_{\mathrm{DC}}/I_{\mathrm{c}} = 0.4$ at $I_{\mathrm{m}} = 12$ A is shown in Fig. 4, where $x = 1.5$ mm is the edge of the strip. It is confirmed from Fig. 4 that the penetration of flux lines with I_{DC} is larger than that without I_{DC}. This result seems to be attributed with the assumption of critical state model in strip superconductors that sheet current in flux lines penetrated region is equal to $J_{\mathrm{c}}d$ where d is the thickness of the strip. Therefore the AC loss with I_{DC} is larger than that without $I_{\rm DC}$.

Fig. 5 shows the result of AC loss for the case of $\gamma = 0.5$ with various $I_{\rm DC}$ for the strip superconductor. The critical current is 340 A and is larger than the previous calculation of 60 A, since the value of γ changes from 1 to 0.5. It is found that the AC loss with $I_{\rm DC}$ becomes larger than that without $I_{\rm DC}$ at small AC amplitudes. The reason for larger AC loss is attributed to the larger penetration depth of the flux lines to the strip superconductors due to the reduction of the critical current density by increasing magnetic field induced by $I_{\rm DC}$ assumed in Irie-Yamafuji model. Since the enhancement of AC loss by addition of $I_{\rm DC}$ is so large, it is recommended that the strip superconductor is used as the cylindrical hollow structure in DC cable. Then the flux lines penetrate mainly from the wide surface of the strip and the AC loss can be reduced and evaluated from the case of the cylindrical superconductor.

4. Conclusions

In this study, the AC losses of ripple current of cylindrical and strip superconductors are numerically investigated by using FEM in which the magnetic field dependence of the critical current density by Irie-Yamafuji model and the n-value model are taken into account. And the calculated results are compared with the theoretical predictions. It is confirmed that the calculation by FEM agrees well with that by the theory for the case of the cylindrical superconductor, and the calculation by FEM is confirmed to be useful. On the other hand, the AC loss with $I_{\rm DC}$ becomes larger than the AC loss without $I_{\rm DC}$ at small AC amplitudes for the strip superconductor. This tendency is already pointed out by Clem for the case of pure AC current, and it becomes more significant for the case of ripple current with DC current, since the critical current density becomes small by the addition of DC current. Therefore it is recommended to use as the cylindrical hollow structure for the strip superconductor to reduce the AC loss.

Acknowledgements

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Table 1: Parameters for cylindrical and strip superconductors in FEM.

	α_c	γ	No. of element	No. of node
cylinder	2×10^8	0.5	2,400	5,061
strip	1×10^{10}	0.5	76,000	105,000

Figure captions

Fig. 1 AC ripple current amplitude dependence of AC loss of ripple current for cylindrical superconductor. Symbols are calculated by FEM. Solid and dotted lines are theoretical predictions [4] for $I_{\mathrm{DC}} = 432$ and 0 A, respectively.

Fig. 2 Magnetic field distribution in cylindrical superconductor with various values of n at $I_{\mathrm{m}} = 324$ A. Red solid line represents the theoretical prediction corresponding to $n = \infty$.

Fig. 3 Normalized AC amplitude dependence of normalized AC loss with various I_{DC} for $\gamma = 1$ in strip superconductor. Red solid line represents the prediction by Norris's theory.

Fig. 4 Magnetic field distribution in strip superconductor for $I_{\mathrm{DC}}/I_{\mathrm{c}} = 0$ (black lines) and $I_{\mathrm{DC}}/I_{\mathrm{c}} = 0.4$ (red lines) from $I_{\mathrm{DC}} + I_{\mathrm{m}}$ to $I_{\mathrm{DC}} - I_{\mathrm{m}}$.

Fig. 5 AC amplitude dependence of AC loss with various I_{DC} for $\gamma = 0.5$ in strip superconductor.

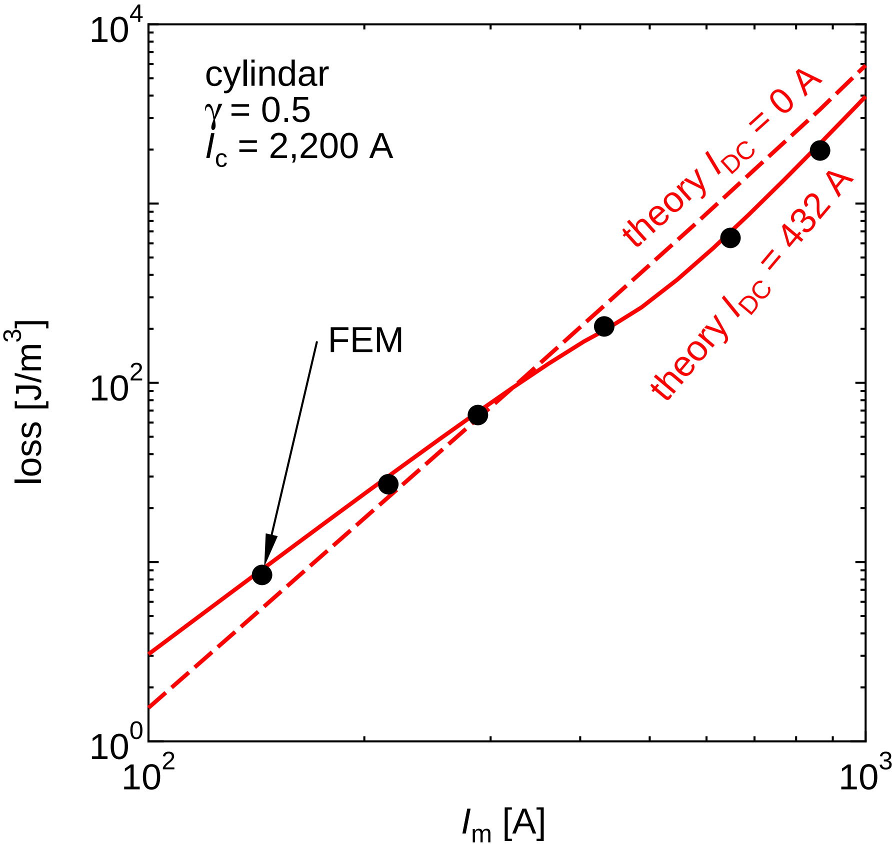
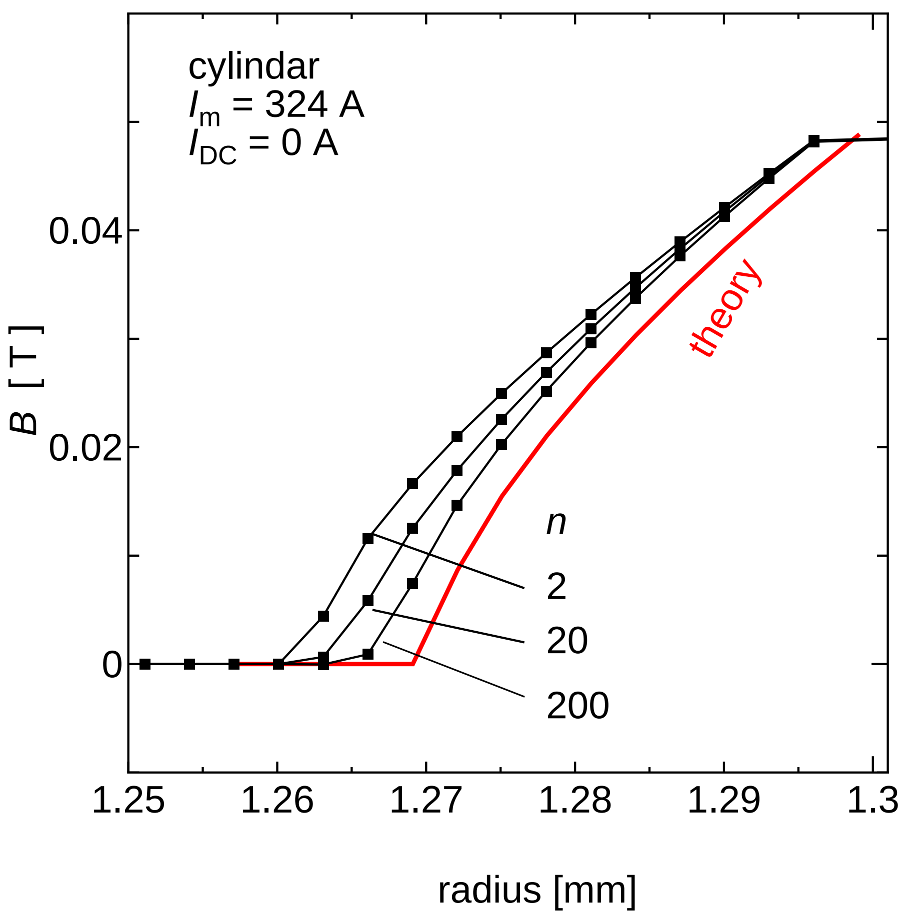


Figure 1: E. S. Otabe *et al.*



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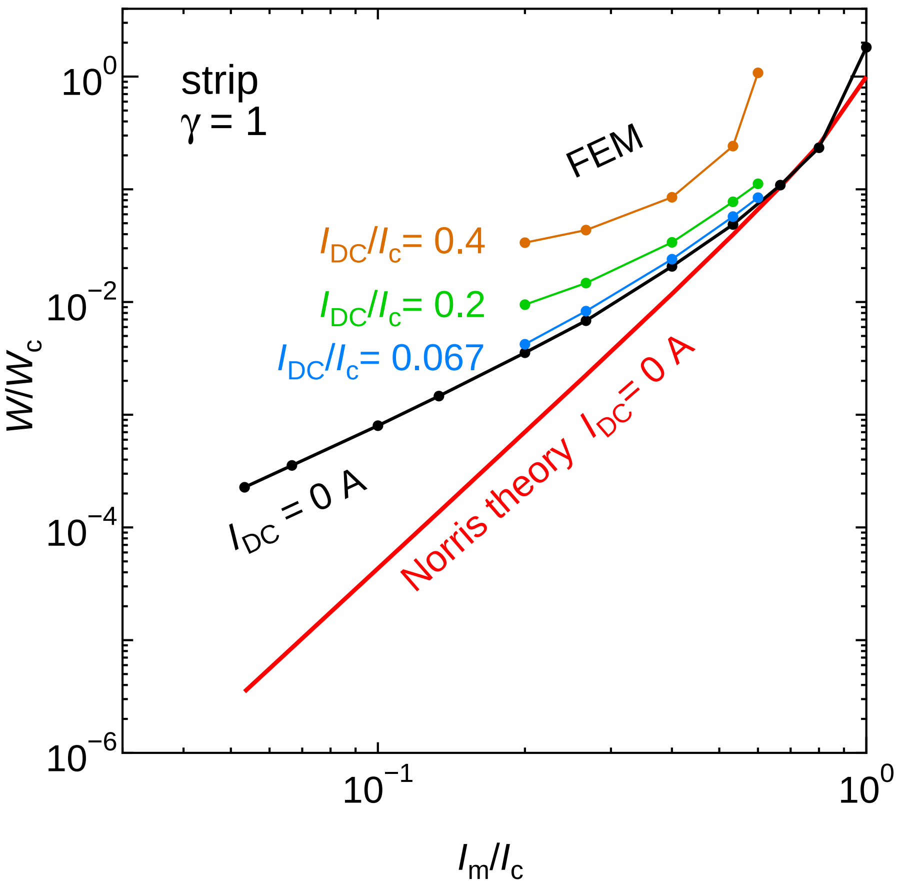

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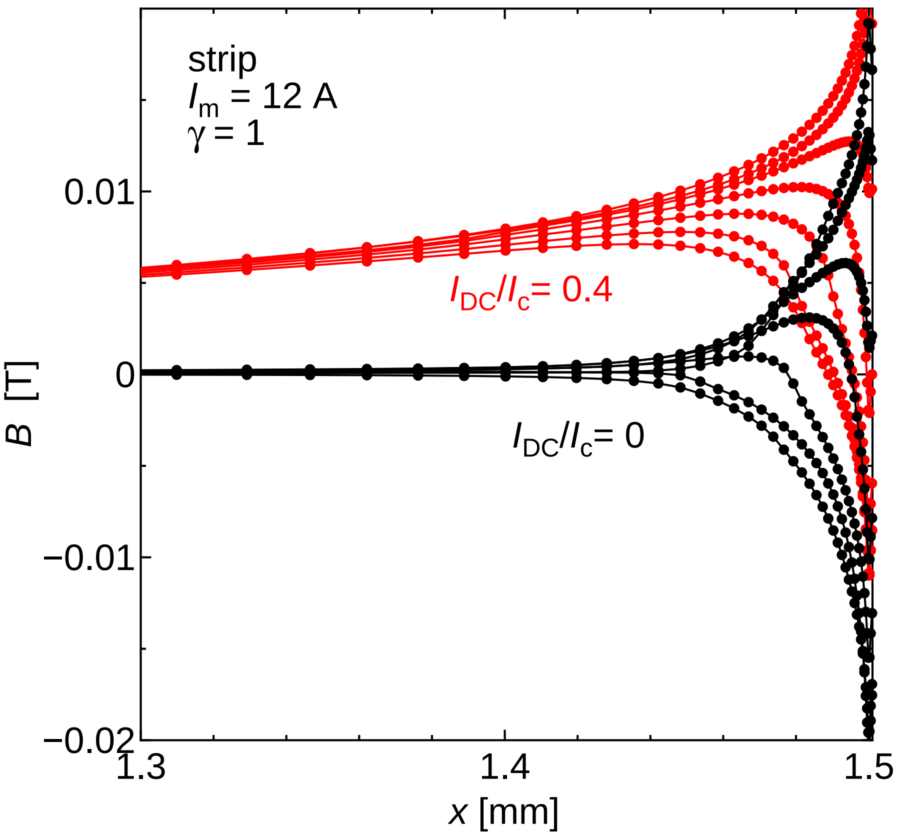

Figure 4: E. S. Otabe *et al.*

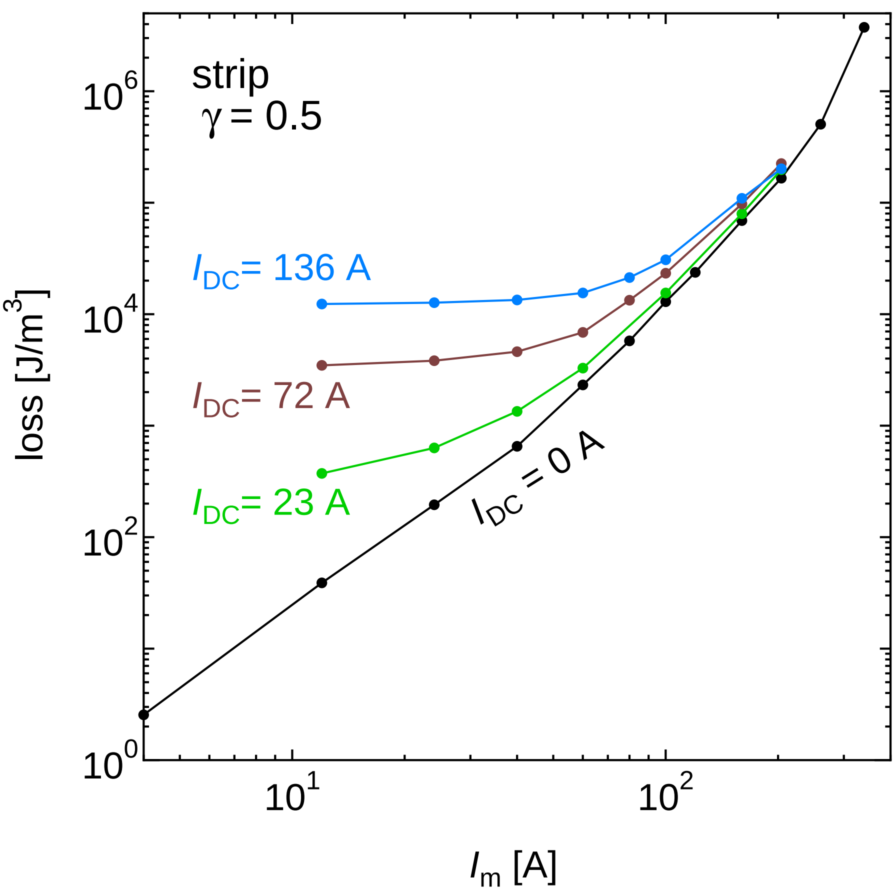

Figure 5: E. S. Otabe *et al.*